A Multiuser, Multicarrier Link Adaptation Strategy for Fading Channels with PER Constraints

M. Nicolaou, S. Armour, A. Doufexi, Y. Sun*
Department of Electrical & Electronic Engineering,
University of Bristol, Bristol, United Kingdom.
*Toshiba Research Labs Europe
M.Nicolaou@bristol.ac.uk

Abstract: **Link Adaptation (LA) adopted by many emerging standards, such as WCDMA, LTE and WiMAX is a key element for providing improved data rates and performance guarantees based on specified Quality of Service (QoS) requirements. Link Adaptation can dynamically adjust a number of transmission parameters, most often modulation and coding, to reflect the characteristics of the wireless link to improve throughput and maintain link reliability. Most LA algorithms require only an estimate of the signal-to-noise ratio (SNR) to select an appropriate PHY mode, relying on the assumption of an AWGN channel. For channels experiencing frequency selective fading however, the conventional approach fails to accurately represent the stochastic nature across independent channels. A new channel quality metric is proposed in this paper that attempts to estimate the likelihood of packet errors in a fading channel and adjust Modulation and Coding Scheme (MCS) selection across each fading realisation independently. Results show improved mode selection efficiency over the conventional LA approach with added flexibility, as this approach is independent of the channel environment, providing a universal solution to LA.**

I. INTRODUCTION

One of the main challenges in wireless systems is to satisfy the ever-increasing demand for high speed data services. Traditionally, communication systems have been designed to accommodate the worst case channel conditions in order to guarantee a given QoS. However, this approach under-utilises the channel resources when the channel is in a good state, resulting in poor spectral efficiency.

LA has been widely used as method of increasing the spectral efficiency of wireless systems. A number of systems, such as enhanced data rates for GSM evaluation (EDGE) [1, 2], high speed downlink packet access (HSDPA) in UMTS, CDMA and WCDMA schemes, LTE and WiMAX [3] provide support for rate adaptation algorithms that enable the adaptation of the modulation and coding rate according to the channel state. LA schemes have the flexibility to adapt a variety of transmission parameters in an attempt to maintain a specific link quality under varying channel conditions. The fundamental transmission parameters that can be adapted include modulation and coding, but additional adjustable parameters can include power levels, spreading factors, signalling bandwidth, antenna configuration etc.

LA schemes can be classified in two distinct categories according to the optimisation criterion. Throughput-oriented algorithms maximise capacity, irrespective of the re-transmission rate arising from packets received in error. Delay-oriented algorithms attempt to minimise re-transmissions by keeping the Packet Error Rate (PER) low. Delay-oriented LA algorithms are therefore more applicable to delay sensitive applications, such as VoIP, sacrificing capacity for the benefit of lower packet re-transmissions and hence lower overall packet latencies.

In wireless channels, received signal quality is affected by a number of physical factors, namely path loss, log-normal shadowing, fast Rayleigh fading and noise [3]. The impact of fading to the physical layer (PHY) performance of wireless channels has been extensively studied in [4-6] for the ETSI/BRAN channel models [7]. By averaging over a number of channel realisations, the average PER performance has been traditionally used for link adaptive MCS selection. The conventional LA strategy relies only on an estimation of the SNR for MCS selection. Under the assumption of some a-priori knowledge of the propagation scenario, SNR mode switching thresholds can be established for either the throughput maximisation or the delay oriented LA algorithm. In [8, 9] it was shown that this conventional approach fails to fully harness the benefits of LA as it fails to account for the non-deterministic nature of fading channels. Selecting the PHY mode based on an average PER curve in a channel affected by multipath can result in significant link 'miss-adaptations' returning a lower than expected throughput and/or higher than predicted packet retransmissions.

Current LA algorithms have been concentrated on a single-user channel scenario with no diversity exploitation. However, as was shown in [10], a higher overall spectral efficiency can be achieved by exploiting the fading nature of wireless channels, in a multiuser environment in an opportunistic scheduling manner. The proposed multiuser diversity (MUD) principle states that by scheduling users only on their strongest channels, and provided different users experience independent fading statistics, a notable increase in the aggregate spectral efficiency can be achieved as a function of the number of users. From a channel quality perspective, by scheduling users only on their peaks, allows for an elimination of deep fades from the aggregate received channel observed by the BS. This effect reduces the non-deterministic nature of fading channels, which can potentially reflect the nature of an AWGN channel.

This paper examines the potential benefits in MCS prediction accuracy of the conventional LA algorithm in the presence of fading channels in a multiuser scenario with MUD exploitation and proposes a new method that attempts to optimise PER prediction across each fading realisation independently. The proposed method shows improved mode selection accuracy, which translates in throughput and QoS improvements.

The remaining of the paper is organised as follows: Section II presents the system model and simulations parameters. Sections III and IV examine the conventional LA algorithm for a single-user and a multiuser scenario respectively. Section V introduces the new LA approach and provides comparison metrics of mode selection efficiency. This paper concludes in Section VI.

II. SYSTEM MODEL

The conventional and proposed LA schemes are examined under a 2x2 MIMO antenna configuration employing OFDMA. It should be noted, however, that the proposed implementation is universal and independent of the multiple access scheme or PHY mode configuration.

An urban micro channel environment is generated based on the extension of spatial channel model (SCME) proposed for LTE [11]. A total number of users, K=20, is assumed where appropriate. Table 1 shows the PHY transmission modes used in the LA process which are similar to the ones considered in [12] for a ‘4G’ system.

A delay-oriented LA approach is the focus in this paper. An upper PER constraint of 10^{-3} is assumed in the MCS process, a value appropriate for VoIP traffic, chosen such that the number of packet retransmissions is kept low [13]. Table 2 presents the key simulation parameters used in this paper.

Table 1: PHY Transmission Modes

Mode	Modulation	Coding Rate	Coded Bits per OFDM symbol	Data Bits per OFDM symbol
1	BPSK	½	768	384
2	QPSK	½	1536	768
3	QPSK	¾	1536	1152
4	16 QAM	½	3072	1536
5	16 QAM	¾	3072	2304
6	64 QAM	¾	4608	3456

Table 2: Simulation Parameters

Parameter	Value
Channel Bandwidth	10 MHz
Operating Frequency	5GHz
FFT size	1024
Data Subcarriers	768
Guard Interval Length	176
Subcarrier Frequency Spacing	10.94 KHz
Useful Symbol Duration	102.9 µS
Channel coding	Punctured $1/2$ rate, convolutional code, constraint length 7, $\{133,171\}_{\text{octal}}$

III. CONVENTIONAL PHY MODE SELECTION OVER FADING CHANNELS

As demonstrated in [8, 13], the conventional MCS selection strategy based on the average PER performance (where the average is obtained across an ensemble of instances of the fading channel response) provides an unreliable estimation of the performance of the instantaneous channel, leading to considerably sub-optimal performance and failure to guarantee QoS for real-time traffic. This is due to the failure of this approach to accurately characterise the instantaneous channel performance, due to the large associated deviation of the average PER curve from the instantaneous samples from which it is comprised.

Two possible MCS miss-adaptation possibilities exist. A non-optimal LA strategy can either over-estimate or under-estimate the current channel. For under-estimation, the LA algorithm predicts that the quality of the current channel state is worse than it actually is, leading to a lower mode being selected than what can actually be supported. Over-estimation occurs when the instantaneous channel quality is worse than what has been predicted by the LA algorithm. A higher mode than what can actually be supported is selected in this case. Under PER constraints, the excessive re-transmissions arising from channel over-estimations can reduce throughput and also result in a failure of the QoS requirements due to the higher than anticipated rate of packet re-transmissions.

Figure 1 illustrates the variation of the packet error rates for the 3GPP-SCM urban micro channel across a number of independent fading samples of the stochastic channel model. Results are based on Mode 4, but the PER distribution trend is consistent for all the PHY modes considered in Table 1. Further, these results show broadly similar trends to the results shown in [8] for different system and channel models. It can be observed that the average PER performance is highly dictated by the few, highly poor channel realisations. Most of the channel realisations have PERs considerably lower that the average. Therefore, for the average PER approach the LA algorithm under-estimates the channel for the majority of channel realisations, providing poor spectral efficiency. In the instances when the current channel quality is over-estimated the chosen PHY mode will be too high, leading to a failure in meeting QoS requirements. The wide range of SNR values for a target PER across different samples helps to highlight the argument that the conventional LA method fails to accommodate the inherent stochastic variability of fading channels. The average PER LA approach will only be accurate for channel instances perform very close to the average PER trend.

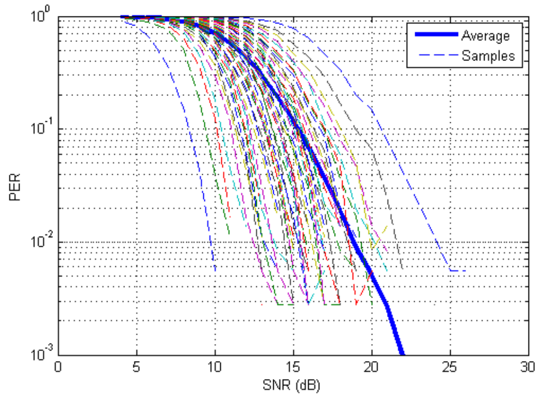

Figure 1: PERs for individual channel samples of the 3GPP-SCM model, 16QAM, 3/4 code

In Table 3 and Table 4 the average and the variance of PER for all PHY modes at various SNR values are presented respectively. The average PER drops as a function of the SNR. The PER variance indicates that there exists a range of high SNR values (high with respect to a specific mode) for which both the average PER and PER variance across different realisations is quite low, leading to consistently good performance, regardless of the fading nature of the channel. For mid-range SNR values the performance is dependent on the fading nature of the particular realisation, making the average PER an unreliable metric for LA.

In [8] the authors proposed that the PER corresponding to a particular realisation should be used for LA purposes. The variance of the transfer function of each subcarrier over the average transfer function is used as an indicator of the quality of the channel. This indicator value can be mapped to a required SNR value for each channel. Depending on the received SNR and the indicator value, the system can identify an optimum mode. The next section extends this analysis to a multiuser environment, and proposes a more appropriate channel quality indicator for a scheme exploiting multiuser diversity (MUD).

Table 3: Average PER

AVERAGE PER	*SNR(dB)*					
MODE	**5**	**10**	**15**	**20**	**25**	**30**
1	0.1139	0.061	$2.8.10^{-4}$	0	0	0
2	0.5202	0.0625	0.028	0	0	0
3	0.9333	0.4855	0.074	0.041	0.003	0
4	0.9878	0.7041	0.1184	0.052	0.002	0
5	1	0.9809	0.7199	0.1627	0.0106	0.003
6	1	1	0.982	0.7196	0.1492	.0082

Table 4: Variance of PER

PER VAR.	*SNR(dB)*					
MODE	**5**	**10**	**15**	**20**	**25**	**30**
1	$1.1.10^{-3}$	$5.9.10^{-5}$	$1.0.10^{-6}$	N/A	N/A	N/A
2	$3.4.10^{-3}$	$9.2.10^{-4}$	$2.2.10^{-5}$	N/A	N/A	N/A
3	$4.3.10^{-2}$	$5.8.10^{-2}$	$4.9.10^{-4}$	$2.7.10^{-5}$	$5.9.10^{-7}$	N/A
4	$3.19.10^{-4}$	$6.4.10^{-2}$	$1.2.10^{-2}$	$5.6.10^{-5}$	$3.1.10^{-7}$	N/A
5	1	1.10^{-2}	1.10^{-3}	$1.1.10^{-7}$	$9.9.10^{-5}$	$7.1.10^{-7}$
6	1	1	1.10^{-3}	$1.1.10^{-3}$	1.10^{-3}	$6.5.10^{-5}$

IV. CONVENTIONAL LINK ADAPTATION IN A MULTI-USER SYSTEM

The benefits of MUD in terms of spectral efficiency are well known and widely investigated in literature, e.g. [14-18]. This section investigates the potential benefits of MUD in terms of improving the MCS selection reliability of the conventional LA approach. By scheduling users on their peaks, deep fades can be effectively removed and the aggregate received channel can closely resemble the performance of an AWGN channel.

In Figure 2 the PER performance of the average and the independent channel realisations is presented, for a scheme exploiting MUD diversity for the channel conditions assumed in Figure 1. A simple rate maximisation scheduling algorithm is employed. A significant improvement of the average PER performance is observed. A similar trend in the distribution of PERs for the individual channel samples is also observed. Most of the samples tend to be better than the average, the average PER performance however, being heavily distorted by a few poor realisations. The dynamic range of required SNRs for different realisations is however much lower than that of the single-user scenario (approx. 5dB as opposed to 14 dB). This range reduction implies a more uniform performance across different realisations, arising from the exclusion of deep fades from the effective received channel. It is expected that for an increasing number of users, the dynamic range of SNR values for a target PER will further diminish due to more efficient MUD exploitation.

To investigate the mode prediction accuracy, LA mode efficiency is defined as the range of SNR values over which the LA strategy correctly predicts the optimum mode over the total SNR operating range. Consequently, the miss-adaptation ratio is defined as the ratio of the range of SNR values for which an incorrect mode is selected over the total SNR operating range. A 'genie' approach [19] is used as a benchmark for the optimal switching mode thresholds. In Figure 3 miss-adaptation ratios, considering over-estimation and under-estimation for 36 independent channel realisations, each comprised of 1000 samples of similar quality is presented. Realisations are ranked in terms of their quality, from best to worst. The conventional LA algorithm is likely to under-estimate the performance of samples with particularly good channel quality. For these channels the miss-adaptation is quite high, and can even result in a complete failure in selecting the optimum mode. As the channel quality of the independent channels converges to the average, efficiency improves. As channels exhibit conditions worse than the average, the adoption of the conventional LA algorithm results in excessive over-estimations. Consequently, the algorithm fails to meet the QoS requirements.

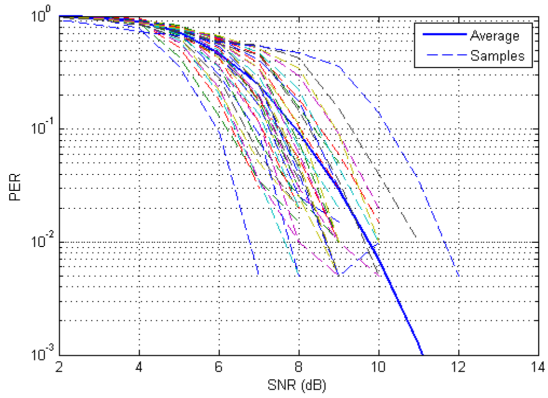

Figure 2: PERs for individual channel samples of the 3gpp-scm model exploiting multiuser diversity, 16QAM, 3/4 code

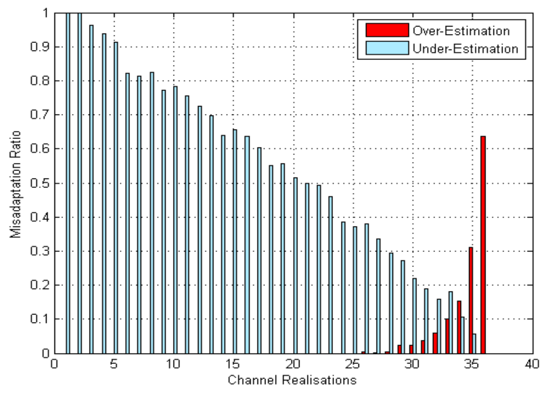

Figure 3: Miss-Adaptation Percentages for Overestimation and Underestimation of PHY modes for conventional LA

Analysis of the conventional LA strategy for a single-user and a multi-user environment has revealed that by excluding deep fades from the resource allocation process via MUD, a more predictable channel performance is obtained, as indicated by the reduction of dynamic range of the required SNR values for a target PER. However, despite the reduced variance in required SNR values across different realisations, significant mode miss-adaptations still occur, leading to considerable performance degradations.

The following section discuses the development of a new LA strategy that promises improved mode selection reliability irrespective of the variations of different channel samples. A channel quality metric developed to more accurately predict the PER performance of each realisation independently is proposed. By having an independent quality metric for each sample, the stochastic variability of the fading channel is incorporated in the MCS strategy, resulting in improved mode selection accuracy.

V. LINK ADAPTATION STRATEGY BASED ON STOCHASTIC CHANNEL VARIABILITY

In [8] a method for indicating the quality of independent channel realisations was proposed. An indicator value, denoting the variance of the average channel response to the individual subcarrier response was used to estimate the likelihood of deep fades.

$$I_{\text{var}} = \frac{1}{N_{sc}-1}\sum_{i}^{N_{SC}}\left(\left|H_i\right| - \left|\overline{H}\right|\right)^2 \qquad (1)$$

where N_{SC} is the total number of data subcarriers, and H_i, denotes the channel response of the i-th subcarrier.

A strong correlation between the variance indicator and the required SNR can indicate the suitability of the indicator metric in characterising channel quality, where channel realisations with low variance require a lower SNR to achieve a target PER. This variance indicator is only suitable for a single-user scenario, as it incorporates assumptions that may not be valid in a multiuser environment. Initially, this metric takes into account only the variance of the channel responses, but does not consider the relative strength of these responses. For a single-user scenario, it can be argued that the average normalised response $\left|\overline{H}\right|$ does not deviate significantly across different channel realisations, and hence does not affect the distribution of PERs for different samples. However, for a scheme exploiting MUD, the effective $\left|\overline{H}\right|$ can vary significantly as a function of the number of users and the scheduling algorithm. Furthermore, the two-norm variance indicator of eq. (1) considers both deep fades as well as peaks as being equally detrimental to the channel quality. Clearly, this assumption does not fully describe the likelihood of bit errors in a fading channel. It is quite possible that an error free transmission can be achieved, in a highly varying channel, if $\left|\overline{H}\right|$ is high. Conversely, a channel with low variance but also low $\left|\overline{H}\right|$ is deprived of strong peaks that would result in the correct transmission of bits encoded on these peaks.

A new fading indicator metric which considers the effect of scheduling on deep fades and estimates the likelihood of bit errors arising from these deep fades in a multiuser environment is proposed in this paper. It is argued that the average received channel strength on the assigned resources of a user k is a strong indication of the likelihood of bit errors Additionally, only the effect of scheduling in deep fades rather than the aggregate variance arising from both fades and peaks, is considered based on a zero-norm distribution. The average received signal strength is represented by the SNR value arising from the received $\left|\overline{H}\right|$ value. The ratio of the number of subcarriers with $\left|H_i\right| < \left|\overline{H}\right|$ over the total number of subcarriers is used as an indication of deep fades as indicated in eq. (2).

A high average SNR value and a small number of frequency responses in a fade describe a received channel with a low likelihood of packet errors. Therefore, realisations with high corresponding fading indicator values are expected to require a lower SNR levels to achieve a target PER for a given MCS.

$$I_{fad} = \frac{\overline{SNR}}{\frac{1}{N_{SC}}\sum_{i}^{N_{SC}}F(i)} \qquad (2)$$

where $F(i)=1$ if $\left|H_i\right| < \left|\overline{H}\right|$ and $F(i)=0$ otherwise, $\left|\overline{H}\right|$ corresponds to the average response across only the assigned resources of each user.

A strong correlation between the fading indicator and the required SNR is observed in Figure 4. For the computation of the fading indicator, ideal channel estimation has been assumed. It can be observed that the fading indicator values obtained from different channel samples represented by the points on the plot can be readily mapped to a required SNR value and approximated by a cubic function, as indicated by the solid, interpolation curve. Cubic equations are determined for every mode offline. By establishing the estimated SNR ranges for each mode, the proposed delay-constraint LA strategy can directly determine the appropriate mode that maximises link throughput under the specified PER requirements.

In Figure 5 the resulting miss-adaptation ratios for the proposed LA algorithm in a multiuser environment are shown. A significant reduction in miss-adaptations over the conventional LA approach can be observed. In addition, higher homogeneity in the range of underestimations and overestimations is observed, independent of the quality of the independent channel samples.

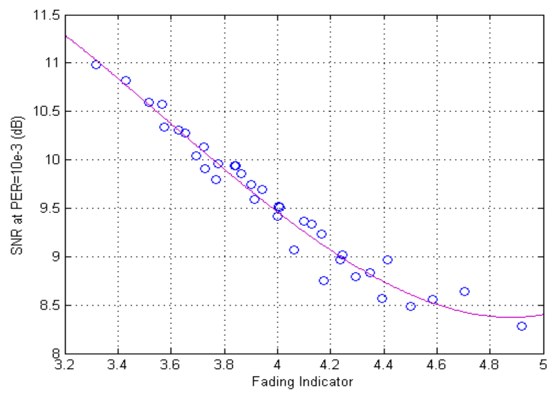

Figure 4: Fading Indicator values for a target PER=10e-3 for a multiuser channel environment. 16QAM, 3/4 coding rate

In Table 5 the mode selection efficiency and the corresponding miss-adaptation ratios of the conventional and the proposed LA method are compared in a multiuser environment (total no. of users K=20) exploiting MUD. It can be observed that a very significant improvement in efficiency is achieved by the proposed LA algorithm based on the fading indicator metric. This is largely due to the reduction in channel under-estimations, which allow for an improvement in the average system throughput. It has to be noted that the calculation of fading indicators is independent of the scheduling approach employed or the number of users. The conventional LA method requires different sets of PER for different channel environments or scheduling approaches, since such factors will invariably affect the average PER performance, resulting in prohibitive complexity. The proposed fading indicator metric is independent of external factors, providing a universal approach irrespective of the channel conditions. Any change in the quality of the received channel response will be directly reflected on the fading indicator value, enabling the same set of cubic equations to be used to determined the optimum MCS for a given SNR for a target PER requirement.

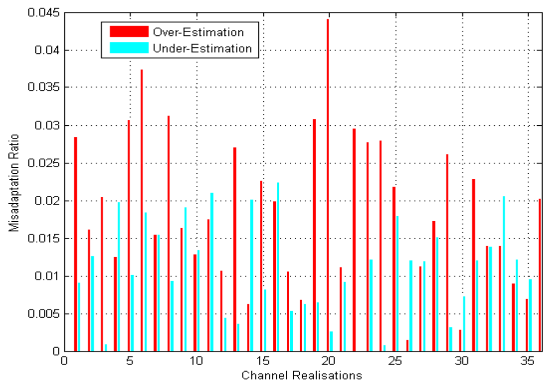

Figure 5: Miss-Adaptation Percentages for Overestimation and Underestimation of PHY modes for proposed LA

Table 5: Link Adaptation Mode Selection Efficiencies

LA Algorithm	Mode Selection Efficiency (%)	Over-Estimation Percentage	Under-Estimation Percentage
Average PER LA	41.89	3.77	54.34
Fading indicator	88.35	6.85	4.8

IV. CONCLUSIONS

Link adaptation strategies applied to fading channels have been considered in this paper. Conventional algorithms are based on the assumption of an AWGN channel and rely solely on the average SNR value of the received channel response for mode selection. The conventional PHY mode estimation approach has shown improved accuracy, by applying this algorithm to a system exploiting multiuser diversity. By effectively removing deep fades from the aggregate received channel, independent channel realisations tend to behave more closely to AWGN. Nevertheless, a large degree of mode miss-adaptations still remain, as demonstrated in this paper. A channel quality indicator, whereby the likelihood of bit errors can be approximated independently for each channel realisation based on a zero-norm distribution of the fading instances of the received channel response has been developed in this paper. The proposed LA scheme significantly outperforms the conventional scheme, both in terms of throughput and reliability, providing the additional benefit of increased robustness and reduced complexity towards dealing with changes in the channel environment or the scheduling strategy, since any change in these parameters will be directly reflected on the fading indicator metric.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support of Toshiba Research Europe Limited.

REFERENCES

[1] "EDGE-Evaluation of 8-PSK," *ETSI SMG2, WPB#4*, Finland April 20-24, 1998, Source: Ericsson.

[2] D. Molkdar, W. Featherstone, and S. Larnbotharan, "An overview of EGPRS: the packet data component of EDGE," *Electronics & Communication Engineering Journal*, vol. 14, pp. 21-38, 2002.

[3] "Air Interface for Fixed and Mobile Broadband Wireless Access Systems," *IEEE Std 802.15e-2005 and IEEE Std 802.16-2004/Corl-2005, Feb 2006*.

[4] S. Armour, A. Doufexi, A. Nix, and D. Bull, "A study of the impact of frequency selectivity on link adaptive wireless LAN systems," IEEE Vehicular Technology Conference, VTC-Fall, 2002.

[5] A. Doufexi, S. Armour, A. Nix, and D. Bull, "A comparison of HIPERLAN/2 and IEEE 802.11a physical and MAC layers," IEEE Communications and Vehicular Technology, SCVT, 2000.

[6] A. Doufexi, S. Armour, M. Butler, A. Nix, and D. Bull, "A study of the performance of HIPERLAN/2 and IEEE 802.11a physical layers," IEEE Vehicular Technology Conference, VTC 2001, Spring.

[7] J. Medbo and P. Schramm, "Channel Models for HIPERLAN/2," *ETSI/BRAN document no. 3ERI086B*

[8] M. Lampe, H. Rohling, and W. Zirwas, "Misunderstandings about link adaptation for frequency selective fading channels,"IEEE Personal, Indoor and Mobile Radio Communications, PIMRC 2002.

[9] F. Tang, L. Deneire, M. Engels, and M. Moonen, "A general optimal switching scheme for link adaptation," IEEE Vehicular Technology Conference, VTC-Fall, 2001.

[10] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *Information Theory, IEEE Transactions on*, vol. 48, pp. 1277-1294, 2002.

[11] D. S. Baum, J. Hansen, and J. Salo, "An interim channel model for beyond-3G systems: extending the 3GPP spatial channel model (SCM)," IEEE Vehicular Technology Conference, VTC-Spring. 2005

[12] A. Doufexi and S. Armour, "Design Considerations and Physical Layer Performance Results for a 4G OFDMA System Employing Dynamic Subcarrier Allocation," IEEE Personal, Indoor and Mobile Radio Communications, PIMRC 2005.

[13] O. Awoniyi and F. A. Tobagi, "Effect of fading on the Performance of VOIP in IEEE 802.11 a WLANs," IEEE International Conference on Communications, ICC 2004.

[14] J. Jang and K. B. Lee, "Transmit power adaptation for multiuser OFDM systems," *Selected Areas in Communications, IEEE Journal on*, vol. 21, pp. 171-178, 2003.

[15] B. C. Jung, T. W. Ban, W. Choi, and D. K. S. A.-D. K. Sung, "Capacity analysis of simple and opportunistic feedback schemes in OFDMA Systems," IEEE International Symposium on Communications and Information Technologies, ISCIT 2007.

[16] E. Y. Kim and J. Chun, "Random beamforming in MIMO systems exploiting efficient multiuser diversity," IEEE Vehicular Technology Conference, VTC-Spring , 2005

[17] R. Knopp and P. A. Humblet, "Information capacity and power control in single-cell multiuser communications," IEEE International Conference on Communications, ICC 1995.

[18] Z. Lin, B. Vucetic, and J. Mao, "Ergodic Capacity of LTE Downlink Multiuser MIMO Systems," IEEE International Conference on Communications, ICC 2008.

[19] S. Simoens. et. al., "Error prediction for adaptive modulation and coding in multiple-antenna OFDM systems," *EURASIP Signal Processing Journal, Special Section: Advances in Signal Processing-assisted Cross-layer Designs*, vol. 86, pp. 1991-1919.